ECG COMPRESSION USING DYNAMIC TREE VECTOR QUANTIZATION IN WAVELET DOMAIN

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Abstract- In this paper, we propose a novel vector quantizer (VQ) in the wavelet domain for the compression of electrocardiogram (ECG) signals. A vector called tree vector is formed first in a novel structure, where wavelet transformed (WT) coefficients in the vector are arranged in the order of a hierarchical tree. Then, the tree vectors extracted from various WT subbands are collected in one single codebook. Finally, a distortion-constrained codebook replenishment mechanism is incorporated into the VQ, where codevectors can be updated dynamically, to guarantee reliable quality of reconstructed ECG waveforms. With the proposed approach both visual quality and the objective quality in terms of the percent of root-mean-square difference (PRD) are excellent even in a very low bit rate. For the entire 48 records of Lead II ECG data in the MIT/BIH database, an average PRD of 7.3 % at 146 bits/s is obtained. For the same test data under consideration, the proposed method outperforms many recently published ones, including the best one known as the SPIHT (set partitioning in hierarchical trees).
Keywords - wavelet transform, vector quantization, tree vector, distortion-constrained codebook replenishment

I. INTRODUCTION

The online storage and transmission of electrocardiogram (ECG) signals are useful in many applications, including the Holter recording and telemedicine. However, the amount of ECG data grows with the increase of sampling rate, sample resolution, recording time, and the number of channels, and gradually becomes a problem in these applications when storage space and bandwidth are very limited. The seriousness of the problem can be relieved significantly if we have an ECG data compression method that is capable of reducing data redundancy and preserving the necessary diagnosis information. This is exactly the goal of ECG data compression techniques proposed in many literatures over the past 30 years.

During the past 30 years, we have witnessed the significant improvement in the coding performance of ECG compression methods [1-6]. To push this performance forward, here we propose a highly efficient ECG compression method by making use of the superiority of wavelet transform (WT) and vector quantization (VQ). In our vector formation process, wavelet transformed coefficients in a hierarchical tree order are taken as the components of a vector called tree vector. The tree vectors extracted from various WT subbands are then collected in one single codebook. This feature is an advantage over traditional WT-VQ methods, where multiple codebooks are needed and are usually designed separately because numerical ranges of coefficient values in various WT subbands are quite different. Furthermore, to preserve necessary diagnosis information in decompressed ECG signals, an online codebook updating mechanism for VQ called distortion constrained codebook replenishment (DCCR) is incorporated in our method.

In Sections II and III, we briefly describe the WT and the VQ with DCCR mechanism, respectively. Then, the proposed coding method, including a novel wavelet tree vector structure, the DCCR, and the overall coding architecture, is given in Section IV. In Section V, the simulation results of MIT/BIH database are presented along with discussions. Finally, a conclusion is given in Section VI.

II. WAVELET TRANSFORM

There are several well-known properties of wavelet transform, such as the spatial-frequency localization, energy compaction, and cross-subband similarity, etc. With these nice properties, WT is recognized as one of the most powerful tools for signal processing. For a one-dimensional signal, each WT level can be realized using two pairs of filter $[l, h]$ and $[\tilde{l}, \tilde{h}]$, where one for decomposition and the other for reconstruction and l denotes a lowpass filter and h represents a highpass filter. For a biorthogonal discrete WT (DWT), the filter pairs have following relationships:

$$h(m) = (-1)^m \cdot \tilde{l}(-m+1)$$
$$\tilde{h}(m) = (-1)^m \cdot l(-m+1)$$

By the n-level wavelet decomposition, the original signal $\mathbf{x}$ is decomposed into $n+1$ subbands, i.e. $\mathbf{x}_{H1}$, $\mathbf{x}_{H2}$, $\cdots$, $\mathbf{x}_{Hn}$, and $\mathbf{x}_{Ln}$. Here and throughout this paper, we adopt the 9/7 tap biorthogonal filters, which were applied successfully for ECG compression [6] and image compression [7].

III. CODEBOOK REPLENISHIMENT VECTOR QUANTIZATION

Vector quantization (VQ) is a powerful source coding technique because quantizing a set of samples (vector) is more efficient than quantizing a sample (scalar) individually. VQ has been an essential constituent in many ECG and image compression algorithms, but the quantization distortion associated with VQ is generally nonzero and varies according to the varying characteristics of an input source. To maintain the diagnostic features in reconstructed waveforms for a wide variety of ECG signals, we adopt the VQ with distortion constrained codevector replenishment mechanism (DCCR). As the name 'DCCR' implies, the distortion is 'constrained' by the pre-predetermined threshold d_{th}, and the insertion of new codevectors and the codebook update account for 'codebook replenishment'. The distortion-constrained nature

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keeps the reconstructed distortion of VQ under controlled and guarantees the preserving of diagnostic information if the distortion threshold is set properly. Many useful DCCR-VQ mechanisms have been proposed. Here, we use a simple yet effective mechanism introduced in [8]:

Let $C_t = \{\mathbf{c}_i, \mathbf{c}_i \in \Re^K, i = 1, 2, \cdots, N\}$ be the codebook at time t, where $\mathbf{c}_i$, K, and N represent the codevector, vector dimension, and codebook size of C_t, respectively. Let $\mathbf{x}_t$ be a K-dimensional input vector for VQ. The principle of DCCR mechanism is to monitor distortion between $\mathbf{x}_t$ and corresponding codevector c_{i^*}, i.e. $d(\mathbf{x}_t, \mathbf{c}_{i^*})$, constantly and see if its value exceeds the distortion bound or threshold d_{th}, where $\mathbf{c}_{i^*} = \arg\min_{c_i \in C} d(\mathbf{x}_t, \mathbf{c}_i)$. If not, as in Fig. 1(a), the index i^* is transmitted or stored to obtain the decoded vector $\hat{\mathbf{x}}_t$. At the same time, the codebook C_t is updated to C_{t+1} in the following manner: $\mathbf{c}_{i^*}$ is promoted to the first position of C_t and all the codevectors in front of it, i.e., $\mathbf{c}_1 \sim \mathbf{c}_{i^*-1}$, are pushed down by one notch. If $d(\mathbf{x}_t, \mathbf{c}_{i^*}) > d_{th}$, as in Fig. 1(b), $\mathbf{x}_t$ or its approximation must be transmitted or stored as $\hat{\mathbf{x}}_t$. In this case, $\mathbf{x}_t$ or the approximation is treated as a new codevector and is inserted to the first position of the codebook C_t, all the original codevectors are pushed down by one notch and the last one is discarded.

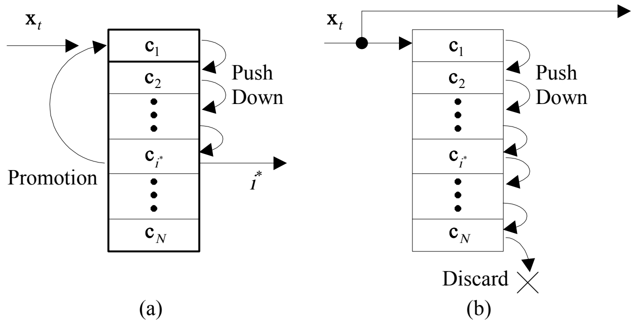

Fig. 1. The DCCR mechanism. (a) $d(\mathbf{x}_t, \mathbf{c}_{i^*}) \le d_{th}$ case. (b) $> d_{th}$ case.

IV. PROPOSED METHOD

A new on-line ECG data compression method based on WT and DCCR-VQ is proposed in this section. The method includes a novel WT based tree structure and the corresponding codevector arrangement for DCCR-VQ. By using the proposed method, we not only require just one codebook for various WT subbands, but also obtain better coding performance.

A. Overview of the Codec

A block diagram of the proposed codec is shown in Fig. 2. First, the t th ECG segment in L-sample long is taken from the original ECG signal S_{ECG} as input vector $\mathbf{x}_t$. Then, an n-level DWT decomposition is performed on $\mathbf{x}_t$, resulting in $n+1$ wavelet coefficient subbands: $\mathbf{x}_{Ln}$, $\mathbf{x}_{Hn}$, …, $\mathbf{x}_{H2}$, and $\mathbf{x}_{H1}$. We extract m tree vectors $\mathbf{x}_{TVj}$, $j = 1, 2, \cdots, m$, from these subbands in a manner to be explained later. For each j, $\mathbf{x}_{TVj}$ is vector quantized to obtain its reconstructed version $\hat{\mathbf{x}}_{TVj}$. The encoded data are decoded through a reverse process as above, resulting in a reconstructed ECG block $\hat{\mathbf{x}}_t$. Continue in this way, the entire reconstructed ECG signal $\hat{S}_{ECG}$ can be obtained on-line.

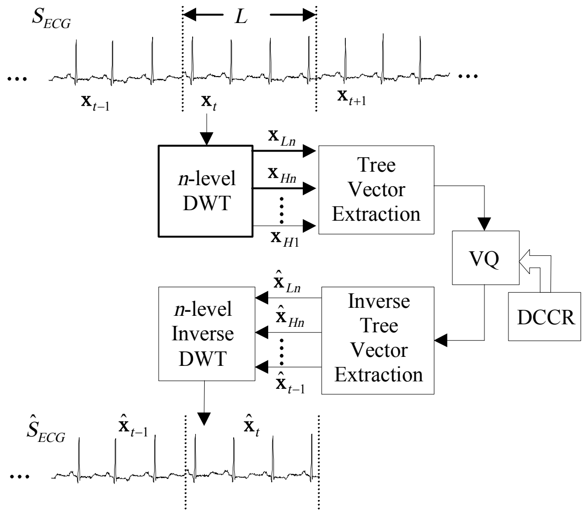

Fig. 2. A block diagram of the proposed codec.

B. Tree Vector Architecture and Corresponding VQ Coder

Given the $n+1$ coefficient subbands, we extract m tree vectors $\mathbf{x}_{TVj}$, where each tree vector is composed of the coefficients taken from these subbands in a hierarchical tree order as shown in Fig. 3. Take the first tree vector $\mathbf{x}_{TV1}$ as an example. The first two coefficient pairs from $\mathbf{x}_{Ln}$ and $\mathbf{x}_{Hn}$, respectively, are assigned to the top and the second layer of the tree vector, respectively. Next, the first 2 and 4 pairs of coefficients from $\mathbf{x}_{Hn-1}$ and $\mathbf{x}_{Hn-2}$, respectively, are assigned to the third and the fourth layers. This process continues until the first 2^{n-1} pairs of coefficients from subbands $\mathbf{x}_{H1}$ are assigned to the bottom layer of the tree vector. This completes the formation of $\mathbf{x}_{TV1}$. For $\mathbf{x}_{TV2}$, the second coefficient pair from $\mathbf{x}_{Ln}$ is assigned to the top layer of the tree vector. Continue in this way and follow the example as above to form $\mathbf{x}_{TV2}$. It is trivial to show that the vector dimension of a tree vector is 2^{n+1}.

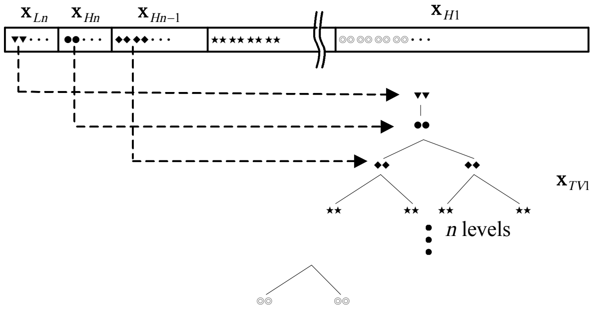

Fig. 3. The hierarchical structure of our tree vector.

Based on this architecture of the tree vector, the corresponding VQ codebook C_{TV} is given and shown in Fig. 4. This special codebook, consisting of N tree codevectors $\mathbf{c}_{TVi}$, $i = 1, 2, \cdots, N$, is available for both encoder and decoder. The C_{TV} can be obtained using any well-known codebook training algorithm, say the LBG.

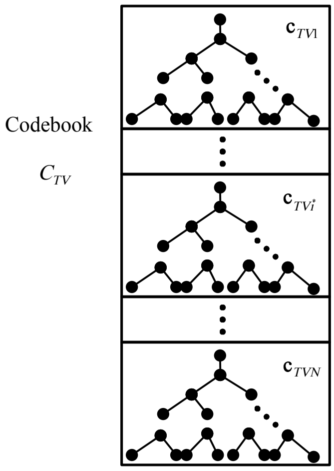

Fig. 4. The tree codebook architecture of the proposed tree codebook.

C. Dynamic Bit Allocation in DCCR Mechanism

Recall that an input vector or its approximation must be sent or stored as a new codevector when $d(\mathbf{x}_{TV}, \mathbf{c}_{TVi^*}) > d_{th}$ in the DCCR mechanism. In this case, the coding efficiency is dropped significantly, especially when n is large. How to increase the coding efficiency in this situation is the key to the success of the proposed method. Since a tree vector $\mathbf{x}_{TV}$ consists of DWT coefficients with great magnitude differences, it is not efficient to assign a fixed number of bits to every coefficient. Therefore, a dynamic bit allocation scheme is needed. Furthermore, the reconstructed distortion does not have to be zero if a nonzero distortion threshold is set, thus it is not necessary to represent the new codevector with a precision more than it should.

With all the considerations above, we found that a DWT-based scalar quantization (SQ) scheme called SPIHT [6] can be a perfect solution to our problem. The SPIHT coding strategy not only performs dynamic bit allocation efficiently according to the magnitudes of wavelet coefficients, but also sends or stores encoded data progressively and can be stopped at the point when the distortion falls within the pre-specified d_{th}. Therefore, we propose a DCCR mechanism with the SPIHT coding strategy as follows.

Case (1): If $d(\mathbf{x}_{TV}, \mathbf{c}_{TVi^*}) \le d_{th}$, the index i^* and a bit "1" indicating case (1) are transmitted or stored. The codebook is rearranged according to the original DCCR mechanism.

Case (2): If $d(\mathbf{x}_{TV}, \mathbf{c}_{TVi^*}) > d_{th}$, the index i^* and a bit "0" indicating case (2) are transmitted or stored. Then, components of the difference vector $\mathbf{e}_{TV} = \mathbf{x}_{TV} - \mathbf{c}_{TVi^*}$ are scalar quantized using the SPIHT strategy to obtain $\hat{\mathbf{e}}_{TV}$. The SPIHT coding process continues until $d(\hat{\mathbf{x}}_{TV}, \mathbf{c}_{TVi^*}) \le d_{th}$, where $\hat{\mathbf{x}}_{TV} = \mathbf{c}_{TVi^*} + \hat{\mathbf{e}}_{TV}$. Finally, the resulting bit stream is transmitted or stored following the bit representation of i^* and the bit "0". Here, $\hat{\mathbf{x}}_{TV}$ is treated as a new codevector and is inserted to the codebook according to the corresponding procedure in the original DCCR mechanism. Note that the SPIHT bit stream includes a 7-bit header to indicate the number of bits to be truncated for decoding. The length 7 is selected here because it is sufficient for all ECG data under consideration based on the experience obtained from the simulation study in the next section.

V. Simulation Results and Discussion

To fully demonstrate the coding performance of the proposed method, a large amount of test data with a wide variety of waveform characteristics is used here. We take all records in full length of Lead II data set from the MIT/BIH arrhythmia database. There are 48 records in the data set and each record is slightly more than 30 minutes long. The sampling rate and the resolution are 360 samples/s and 11 bits, respectively. The numerical values of these ECG data are in the range from -1024 to 1023. Note that we have subtracted the 1024 from the original data ranging from 0 to 2047 in order to comply with the well-known root mean square difference (PRD) criteria in % [6]. In addition, the compressed data rate (CDR) [5] in bits/s or bps is used to evaluate the coding efficiency of the ECG compression method

In this paper the segment length $L = 1024$, vector dimension $K = 64$, codebook size $N = 1024$ and the 6 levels DWT with biorthogonal 9/7-tap filters are adopted here. The results in terms of PRD and CDR are depicted in Fig. 5(a) with various d_{th}'s. Since initial VQ codebooks are all trained using Rec. 100, each point in Fig. 5(a) is an average result of one inside test and 47 outside tests of VQ. We select the

$d_{th} = 60$ case from Fig. 5(a) to show the individual PRD of each record and its corresponding CDR in Figs. 5(b) and 5(c), respectively. The average PRD of all records is 7.3% at 146bps in this case.

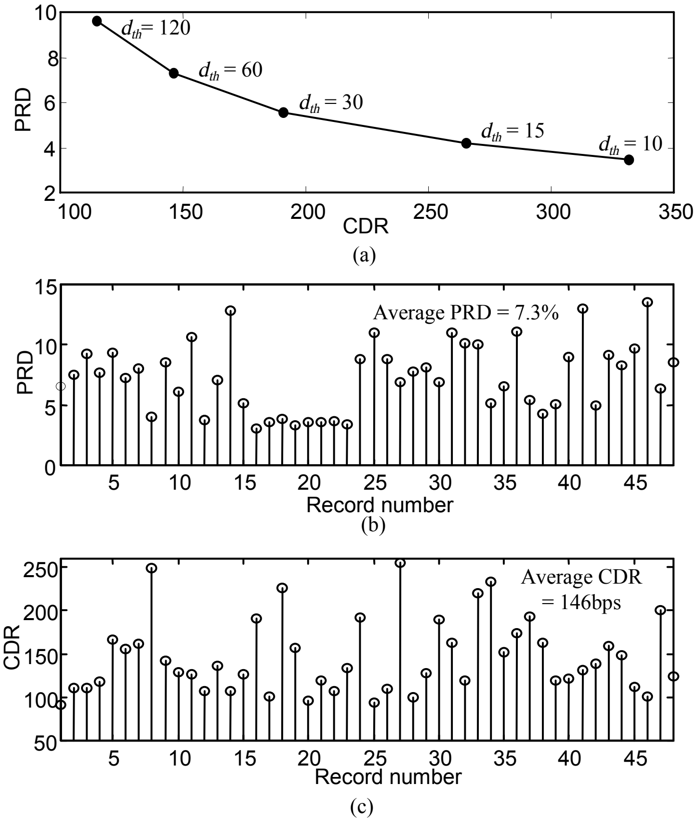

Fig. 5 Coding performances of the proposed approach using all 48 records in the MIT/BIH database as the test data. (a) Average performance of all records using codebook size N = 1024 with various distortion threshold d_{th}; (b) Individual PRD values for each record with $d_{th} = 60$; (c) Individual CDR values for each record with $d_{th} = 60$.

Recently, the SPIHT scheme demonstrates its excellent coding performance in ECG compression [6]. In fact, the performance is so good that hardly any other recently published methods can compete with it. Since it is also a wavelet based coding strategy, it is implemented here for comparison. In [6], the authors test their methods using 11 MIT/BIH records, including Records 100, 101, 102, 103, 107, 109, 111, 115, 117, 118, and 119. We use the same test records in full length (slightly exceeds 30 minutes) instead of 10-minute long used in [6]. In addition, we adopt the same coding parameters of SPIHT as in [6], including 1024 samples in a segment and 9/7 tap biorthogonal filters. The average results are listed in Table I. Note that the coding performances of SPIHT are slightly better than originally given in [16] and it is mainly due to the use of longer test data. Nevertheless, given the same CDR, our PRD performances are superior to theirs in all cases.

TABLE I.
PERFORMANCE COMPARISOM BETWEEN SPIHT AND OUR METHOD

CDR (bits/s)		94.7	112.3	140.5	181.9	246.6	304
PRD (%)	SPIHT	16.9	13.2	9.4	6.3	4.1	3.2
	Our Method	9.8	8	6.1	4.7	3.5	2.9

VI. CONCLUSION

A WT-based ECG coder using a novel hierarchical tree vector and the DCCR mechanism in VQ is proposed. The proposed coder has several advantages over traditional WT-based VQ coders. Firstly, only one single codebook is required for various WT subbands. This advantage greatly reduces the design difficulty in determining good codebook sizes and codevector dimensions for multiple codebooks. Secondly, the distortion of reconstructed signal is bounded. This function is very useful for quality sensitive applications, including ECG signals. Thirdly, an online dynamic bit allocation strategy is incorporated in the DCCR mechanism. This efficient strategy greatly enhances the coding performance of the coder. With the proposed method and its associated advantages, a practical ECG coder with super high coding performance in terms of objective and subjective criteria is demonstrated in the simulation study.

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